

## COASTAL SURFACE CURRENT VARIABILITY

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### LONG-TERM GOAL

The goal of the research effort is to study the effects of Gulf Stream and Florida Current intrusions and tides over the continental slope on coastal surface current variability detected from the Ocean Surface Current Radar (OSCR). A key aspect of the research is to understand the role of subsurface structure on surface current signatures in the internal wave band.

### SCIENTIFIC OBJECTIVES

Specific objectives of the research are to:

1. Relate Interferometric Synthetic Aperture Radar (INSAR) images of internal waves to the high frequency band oscillations found in OSCR fields including the internal wave strain rates and place them into a framework based on K-dV solitary wave theory;
2. Characterize time-space scales of the vertical structure current changes observed by OSCR, moorings and repeat track current profiles, and mooring data including comparisons of the vertical wavenumber spectra from ADCP profiles (with OSCR surface currents) to GM75 spectra;
3. Examine the mean flow shear and vorticity to determine their role on forcing internal waves; and
4. Resolve the surface and subsurface tidal response, and relate differences in the semidiurnal tidal amplitudes to internal tides near or at the shelf break.

### APPROACH

The OSCR system has been deployed in several venues including Cape Hatteras for the HIRES-2 experiment (Shay, et al., JAOT, 1995), OPRC Experiments along the Florida Keys (Shay, et al., JGR, 1997), and in the DUCK94 Experiment (Shay, et al., JAOT, 1997; Cook and Shay, AMS Proceedings, 1998). The system consists of two HF radar transmit/receive stations operating at 25.4 MHz to acquire gridded surface current and Doppler spectra data over a 30x40km region with a spatial resolution of 1.2 km at a sampling interval of 20 minutes. The radar approach is based upon the observation of the first-order Bragg return in the Doppler spectrum from gravity wavelengths of about 6 m; and, in the presence of a surface current, the frequency of the Bragg return is further shifted by an amount proportional to the radial current. Two transmitters/receivers perform as a phased array that utilize beam-forming techniques to isolate the ocean area where scattering occurs within the domain in resolving the radial and the surface current vector. Radial and vector surface current fields and the Doppler spectra are digitally recorded for subsequent processing and analyses.

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Surface currents are treated as quasi-independent estimates at each of the 700 cells, which are then combined with subsurface mooring data and ship transect measurements to examine the relationships between surface and subsurface current structure, particularly in the internal wave band. Data quality is assessed using conventional statistical measures such as regression analysis and kinetic energy spectra. For example, measurements from the Duck94 experiment revealed *rms* differences of  $7 \text{ cm s}^{-1}$  between the surface and subsurface (4 m) currents from Vector Measuring Current Meters (VMCM) (Shay et al., JAOT, 1997). The observations are at the uncertainty limits of resolvable processes from the OSCR and VMCM instruments.

Peaks in the rotary kinetic energy spectra are used as a guide in isolating physical processes in the current signatures. A key element in identifying coastal current variability is the tidal influence. Tides are a source of current variability in the coastal ocean, and may in some instances contribute to the internal wave variability. Sea level records are used as a guide to the tidal constituents used in the harmonic analysis of the current measurements of finite duration. These constituents, which are removed to form detided records, are decomposed into the low-frequency ( $> 48 \text{ h}$ ), inertial, high-frequency and residual currents using digital filtering.

## TASKS COMPLETED

The following list tasks completed:

1. Comparisons to subsurface measurements have been completed from various experiments using methods described above;
2. Sea-level variations have been analyzed for tidal constituents and applied to the surface current measurements;
3. Detided current time series have been digitally filtered to isolate physical processes such as the low-frequency and internal wave band current signatures; and
4. Empirical orthogonal eigenfunction analysis have been performed on the spatially evolving time series to examine horizontal structure variations.

## RESULTS

From the decomposed surface and subsurface current fields during HIRES, the EOF analysis using the real-vector approach on the surface current data resolved the tidal and Gulf Stream flows than those using the complex EOF. That is, the real-vector results indicated more realism in the results such as cross-shelf tidal propagation and closed-loop eddy structures on the shelf (Kaihatu, et al., JAOT, 1997).

On 20 June, the NASA JPL Interferometric SAR was flown during the HIRES-2 experiment (Thompson, et al., EOS, 1994). The INSAR surface current image indicated 200 m, 1 km and 5-6 km wavelength oscillations in the image. High-pass filtered surface currents from below, above and the center of the image as well as the averaged value indicated a significant correlation to the 5-6 km wavelength over this INSAR image. Time/space cross-section of the high-pass filtered velocity components over this period of time revealed phase propagation towards the south for a 6 km wavelength oscillation, which was consistent with the INSAR image. Given the frequency of the oscillation of about 4 h and a wavelength of about 6 km, the corresponding phase speed was about  $0.4 \text{ m}^{-1}$  which was within the range from the available CTD data. For low phase

speeds, the residence time of these oscillations is about 8 data cycles whereas for more typical phase speeds on the shelf, the residence time in an OSCAR cell is about 2 cycles (Shay, AMS Proceedings, 1996).

From a ten-day period during the OPRC-2 experiment, submesoscale vortices located along the inshore side of the Florida Current were aligned with the 150 m isobath (see Figure 1a). Based on the observed surface current images, these submesoscale vortices translated from the western part of the domain towards the eastern part at a rate of  $30 \text{ km day}^{-1}$ . While low-frequency flows indicated little evidence of these features, these observed vortices were embedded in the near-inertial flows, which represents the low-frequency end of the internal wave spectrum (see Figure 1b). Based on a series of least-square fits, the horizontal wavelength of the motions was about 40 km with velocities of up to  $30 \text{ cm s}^{-1}$ . Their vertical structure at the ADCP mooring indicated vertical wavelengths of 45 to 50 m suggestive of a second baroclinic mode dependence (Shay, Oceanogr. Soc., 1997). High-frequency motions were also observed with periods of 4 to 5 h where the vertical wavelengths were 20 to 25 m with horizontal wavelengths of 3 to 5 km. These energetic signals ( $20 \text{ cm s}^{-1}$ ) were associated with soliton-like wave packets forced by the tides at the shelf break.

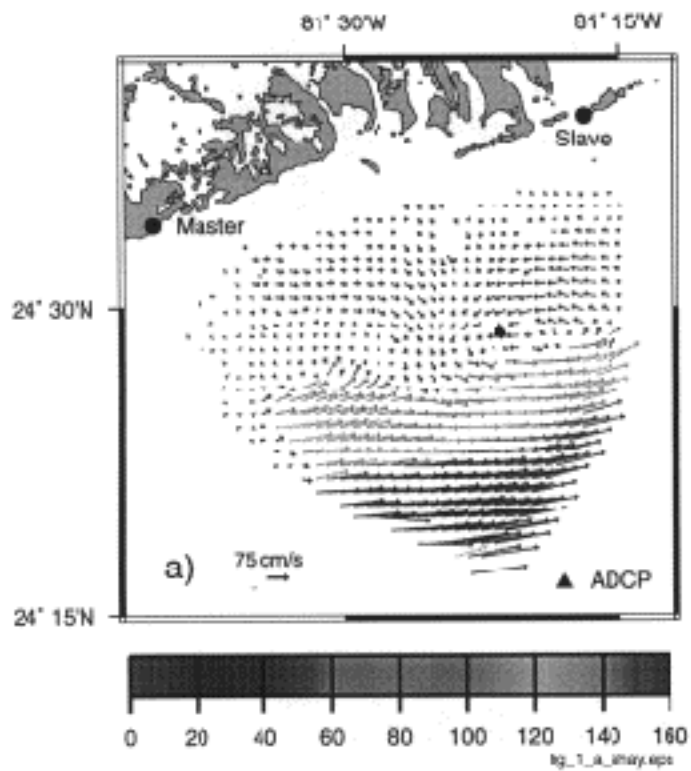
During the DUCK94 experiment, the semidiurnal ( $M_2$ ) tidal constituent dominated the tidal variability (see Figure 2). Cook and Shay (AMS Proceedings, 1998) found a predominately cross-shelf tide propagation, with more of an along-shelf component close to shore. A similar situation existed for the  $S_2$  tide, however it had enhanced amplitudes in the near-shore regime, a minimum in the mid-shelf area, and then increasing further offshore. The  $S_2$  also exhibits more along-shelf variability compared to the  $M_2$  constituent. The rotation of these ellipses was primarily clockwise, and maintained their ellipticity over most of the domain. The decreasing amplitude and phase with depth were consistent with theoretical models of frictional effects on the vertical structure of tidal currents. A large component of the tidal flow was barotropic at least at the two current meter moorings at 20 and 25 m (Shay, et al., JAOT, 1997). The  $K_1$  and  $O_1$  constituents were less important as compared to the  $M_2$  constituent, but comparable in magnitude to each other. Both diurnal constituents varied in amplitude in the along-shelf direction where the ellipse orientations also indicated cross-shelf propagation on the inner shelf, and turn in the along-shelf direction further offshore.

## IMPACT/APPLICATION

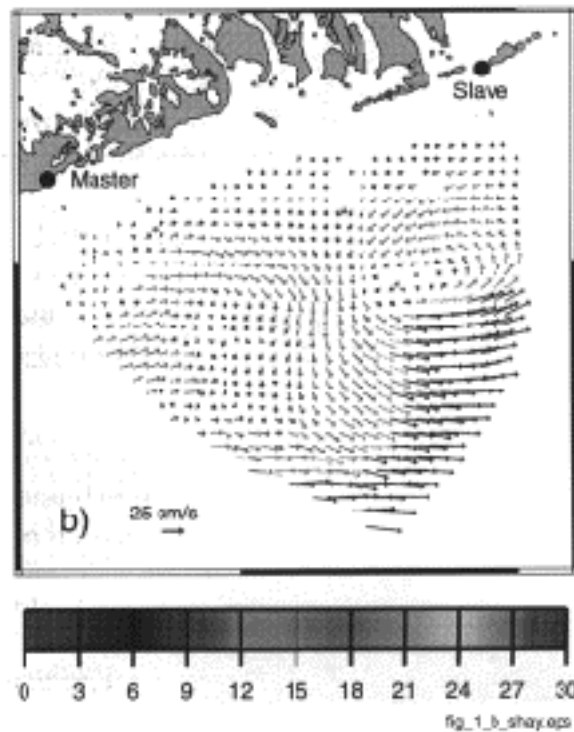
The long-term impact of this research will be: (a) to improve our understanding of surface processes over submesoscale to mesoscale that directly affect satellite-based remote sensing; (b) to examine the effects of subsurface structure and internal wave oscillations on the ocean's surface and the subsequent detection by SAR; and (c) to understand the 3-dimensional circulation patterns in the coastal ocean using remotely sensed and *in situ* data.

## TRANSITIONS

The surface current measurements from HIRES have been provided to ONR/NRL supported investigators for observational and numerical studies encompassing a broad spectrum of processes. The spatially-evolving fields will be eventually provided to the research scientists for observationally-based model studies related to Coupled Oceanic and Atmospheric Mesoscale Prediction System and the Coastal Ocean Remote Sensing Programs at the NRL.



a)



b)

Figure 1. a) Observed and b) Near-Inertial Surface Flows From the OPRC-2 experiment in the Florida Keys at 1800 UTC 25 May 1994. The Color of the Arrows Represents the Strength of the Current Bars in  $\text{cm s}^{-1}$ .

## RELATED PROJECTS

The OSCR deployment during HIREs was jointly supported by ONR Remote Sensing and MMS North Carolina Coastal Physical Oceanography Programs. This observationally-based oceanographic research project also has relevance to ONR Coastal Dynamics, Physical Oceanography, Underwater Acoustics and Oceanographic Modeling and Prediction for basic and applied research initiatives. Ongoing research programs such as COAMPS at the NRL, NSF CoOP, and ONR/NRL Chesapeake Bay Outfall Plume Study have benefited from this program.

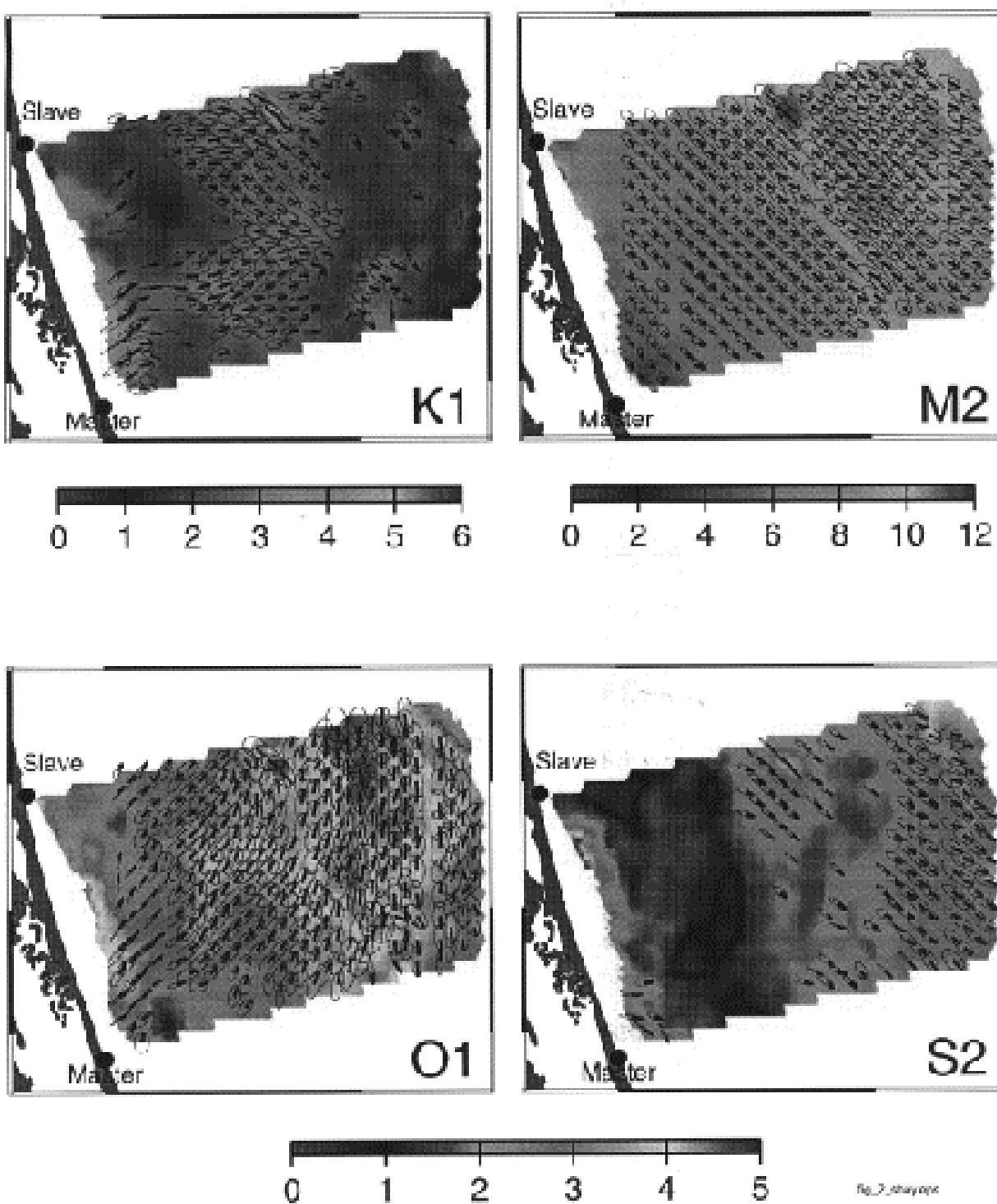


Figure 2. Spatial Distribution of Tidal Ellipses for the Diurnal (K<sub>1</sub>, O<sub>1</sub>) and Semidiurnal Constituents (M<sub>2</sub>, S<sub>2</sub>). Greyshades are Constituent Amplitudes in cm s<sup>-1</sup>. According to Respective Color Bar, Ellipses Trace the Path of Vector W for an OSCR cell with Amplitude Greater than 2 cm s<sup>-1</sup>, and Vectors Refer to Semi-major Axis.